5.0 Agriculture and the Environment: Interactions with Climate

5.1 Introduction

Many previous assessments of the potential impacts of climate change and variability on agriculture have focused solely on agricultural production, food prices, and farm incomes. However, our nation's interest in agriculture is broader than these issues. People in both rural and urban areas value agricultural land as open space and as a source of countryside amenities. Agricultural land is an important habitat for many remaining wildlife species. Agriculture is also a source of negative environmental impacts in some areas. Nutrients, pesticides, pathogens, salts, and eroded soils are leading causes of water quality problems in many parts of the United States. In many parts of the western U.S., agriculture is a major user of scarce irrigation water. In addition, our nation has an interest in agriculture because of its potential to serve as a sink for greenhouse gases.

Agriculture has a number of environmental impacts, some occurring on the farm and others off the farm. For example, cultivation of crops increases the exposure of the land to the forces of wind and water erosion, which has on-farm and off-farm effects. Soil erosion reduces on-farm soil productivity by depleting soil nutrients and altering the structure of the soil in ways that reduce the soil's capacity to infiltrate and hold water. However, farmers themselves are the ones who bear the costs of lower soil productivity in the form of diminished production and sales. Similarly, farmers are the ones who bear the costs of actions to reduce soil erosion (leaving aside government programs that partially subsidize the costs of soil conservation measures). As a result, farmers have a direct financial stake in the on-farm impacts of soil erosion and other environmental problems.

The off-farm environmental impacts of agricultural production, such as surface water sedimentation from eroded soils, are an entirely different matter. These impacts usually never show up on any farmer's bottom line. Farmers may be as concerned about the environment as anyone else, or even more concerned, but it is asking a great deal to expect them to voluntarily reduce their own incomes for the sake of protecting the environment. This is particularly true when they have no reason to believe that their fellow farmers will follow suit.

For these reasons, the off-farm environmental impacts of climate change could be more important from a public policy perspective than impacts on agricultural production, food prices, or farm incomes. Farmers¾as well as seed companies, fertilizer distributors, and other firms that sell products and services to farmers¾will have strong financial incentives to adapt to climate change by minimizing negative impacts on production and exploiting positive impacts. For off-site effects of agricultural practices where environmental and conservation "goods" are not priced in markets, it will be up to federal, state, and local governments to decide if environmental regulations need to be strengthened if climate change worsens environmental problems.

It was beyond the scope of the Agriculture Sector Assessment to consider all of the possible agriculture-environment interactions and how they might be affected by climate change. Much more research and model development is needed on these interactions before the capacity exists to quantitatively and completely assess them. Whereas with market impacts, relatively well developed data on current conditions exist, for environmental concerns we often have very incomplete information on the extent of current problems and their causes. We considered some specific case studies that help illuminate the environmental risks that climate change may present. In most cases, we sought to produce new, quantitative results with models that allowed us to simulate results using the Hadley and Canadian Center climate scenarios used elsewhere in the assessment. The hazard with case studies is that the cases may not be at all representative of what might happen elsewhere or under different climate conditions. Indeed, many environmental problems depend on very specific and precise dimensions of climate. Erosion and runoff is highly nonlinear with rainfall intensity. There may be little or no erosion with moderate storm events with most erosion occurring during one or two extremely heavy and intense storms. Similarly, water recharge and water supply is highly dependent on regional predictions and the specific character of rain events.

The issues we considered were the relationship between agriculture and water quality in the Chesapeake Bay region (Abler, Shortle, and Carmichael, 2000), the potential changes in pesticide use that might occur as a result of changing climate (Chen and McCarl, 2000), the interaction of urban and agriculture demand for groundwater in the Edwards' aquifer region near San Antonio, Texas, (Chen, Gillig and McCarl, 2000), and the potential impacts of climate change on soils (Paul, 2000). These are important environmental issues in their own right. In addition, each of these environmental and conservation concerns are quite different from a physical, biological, economic, and policy perspective, illustrative of the range of environmental and conservations issues that would be affected by climate change.

The Chesapeake Bay is one of the nation's most valuable natural resources, but it has been seriously degraded over the years by agricultural production and other human activities. Section 5.2 analyzes the potential impacts of climate change on nutrient run-off into the Chesapeake Bay, based on new results from an integrated economic-environmental model of corn production in the Bay region. Nutrient run-off during heavy rainfall is the primary mode through which corn production affects the Bay. This is a case of an environmental externality related to agricultural production. There are no direct market incentives for farmers to control runoff of residues into the Bay and the Bay is an open access, public resource.

Section 5.3 examines the interaction between climate change and pesticide use. This section addresses how changes in climate might alter pest populations and in turn the costs of pest treatment. The effects of pests and the decisions to control them are decisions internal to the farmer's decisionmaking and the incentives to control pests are market driven. Pesticide use raises many environmental concerns, from residues on food, contamination of water, and consequences for wildlife. We, therefore, consider here the extent to which climate change could change the use of pesticides. We do not attempt to relate the change in pesticide use to particular changes in exposure of people or wildlife to these chemicals nor do we consider all chemicals used on all crops. To do so is an immense task. Attempts to estimate the relationship between current levels of chemical use and exposure levels are highly uncertain. Even with known levels of exposure, the health and ecosystem effects are highly uncertain. Never-the-less, we believe the results are suggestive of the possible direction of environmental effect.

Section 5.4 considers intersectoral water reallocation in the water scarce region around San Antonio, Texas. Groundwater is a resource that often is not well-managed, although recognition that uncontrolled access to groundwater will lead to excessive depletion has increasingly led States in the arid regions of the countries that rely on groundwater to step in and manage withdrawals. Drawdown of water levels in aquifers can have effects on wetlands and water levels in rivers and lakes thereby threatening wildlife and recreation as well as increase the cost of pumping water for urban and agricultural users. Climate change can affect both the demand for water and the recharge rate of the aquifer.

Section 5.5. examines the interactions between climate change and soil properties. This section discusses the many interactions of soil and climate, including the relationship between soil organic matter and climate. Soil organic matter is largely carbon and, hence, the effects of climate on soil organic matter is a feedback into the climate system. Increases in soil organic matter reflect removal of carbon dioxide by plants and the incorporation of the residue into the soil. Decomposition of organic matter, on the other hand, release carbon back into the atmosphere. The rate of decomposition versus incorporation of organic matter determines whether the soil of a given area is a net source or net sink for carbon. Increases in organic matter, itself, improves soil quality, is a source of nutrients, and thus can improve productivity of crops. The principal goal of this section, however, is to discuss the many ways that climate affects soil and hence the productivity and sustainability of agricultural production. Soil quality in terms of crop productivity is largely an on-site issue where farmers would normally have the incentive to maintain soil quality in an economic manner. There remains considerable uncertainty about the cropping practices that best maintain soil and the long-term effect of existing practices. With this lack of information, there is a need for information, technical assistance, testing, and monitoring so that farmers can better manage their soils toward their own interest of maintaining the long-term profitability of their farm.

5.2 Agriculture and the Chesapeake Bay

We present results of the Chesapeake Bay case study in this section. We begin with an overview of the Chesapeake Bay region, then consider agriculture as it currently exists in the region, sketch a possible future for agriculture in the region, and identify how climate may change in the region. With this background we then briefly describe the simulation model developed and used to investigate the impacts of climate, present the principal results, and conclude this section with some implications for current decisions.

5.2.1 Introduction

The 64,000 square mile Chesapeake Bay watershed is the largest estuary in the United States (Chesapeake Bay Program, 1999). The watershed includes parts of New York, Pennsylvania, West Virginia, Delaware, Maryland, and Virginia, as well as the entire District of Columbia. Over 15 million people currently live in the Chesapeake Bay watershed.

The Chesapeake Bay is one of the nation's most valuable natural resources. It is a major source of seafood, particularly highly valued blue crab and striped bass. It is also a major recreational area, with boating, camping, crabbing, fishing, hunting, and swimming all very popular and economically important activities. The Chesapeake Bay and its surrounding watersheds provide a summer or winter home for many birds, including tundra swans, Canada geese, bald eagles, ospreys, and a wide variety of ducks. In total, the Bay region is home to more than 3,000 species of plants and animals (Chesapeake Bay Program, 1999).

Human activity within the Chesapeake Bay watershed during the last three centuries has had serious impacts on this ecologically rich area. Soil erosion and nutrient runoff from crop and livestock production have played major roles in the decline of the Chesapeake Bay. The Chesapeake Bay Program (1997) estimates that agriculture currently accounts for about 39% of nitrogen loadings and about 49% of phosphorus loadings in the Chesapeake Bay. This makes agriculture the single largest contributor to nutrient pollution in the Chesapeake Bay. Other contributors include point sources such as wastewater, forests, urban areas, and atmospheric deposition.

Agriculture within the Chesapeake Bay region is also a major source of pollution when compared to agriculture in other parts of the country. Of 2,105 watersheds (defined at the 8-digit hydrologic unit code level) in the 48 contiguous states, watersheds in southern New York, northern Pennsylvania, southeastern Pennsylvania, western Maryland, and western Virginia rank in the top 10% in the U.S. in terms of manure nitrogen runoff, manure nitrogen leaching, manure nitrogen loadings from confined livestock operations, and soil loss due to water erosion (Kellogg et al., 1997). Watersheds in southeastern Pennsylvania also rank in the top 10% in the U.S. in terms of nitrogen loadings from commercial fertilizer applications (Kellogg et al., 1997).

This section examines agriculture in the Chesapeake Bay region, both as it exists today and as it might evolve in the first few decades of the 21st century. It also examines the potential impacts of climate change on agriculture and water quality in the Chesapeake Bay region, based on new results from an integrated economic-environmental model of corn production in the Chesapeake Bay region.

5.2.2 Agriculture in the Chesapeake Bay Region

Compared to many other parts of the U.S., agriculture in the Chesapeake Bay region is characterized by smaller farms and a wider range of crops and livestock products. Average farm size in the Chesapeake Bay region is less than 200 acres, compared with over 500 acres for the rest of the country (USDA National Agricultural Statistics Service, 1999). However, poultry and hog operations within the region tend to be as large and intensive as those in other parts of the country (USDA National Agricultural Statistics Service, 1999).

Major sources of farm cash receipts within the Chesapeake Bay region include dairy products, poultry, eggs, hogs, mushrooms, other vegetable and nursery products, apples, and peaches. There is also significant production of corn, soybeans, and hay, but these commodities are mainly consumed on the farm as livestock feed rather than sold.

Due to historically adequate supplies of rainfall in most years, crop production in the Chesapeake Bay region is overwhelming rainfed rather than irrigated. Less than 3% of crop acreage in the region is irrigated, compared with about 13% in the rest of the U.S. (USDA National Agricultural Statistics Service, 1999).

Forests are the largest category of land use in the Chesapeake Bay region, accounting for about 60% of total land use. Agriculture is the second largest category, accounting for nearly 30% of total land use. Urban areas, residential areas, wetlands, and other land uses account for the remainder. Production agriculture accounts for about 2% of the total labor force in the Chesapeake Bay region.

5.2.3 Future Agriculture in the Chesapeake Bay Region

Agriculture in the Chesapeake Bay region, like U.S. agriculture as a whole, has changed radically during the last century, and there are few reasons to expect this rapid pace of change to slow down. With the notable exception of the Amish, tractors and other farm machinery have virtually eliminated the use of draft animals and have made it possible for a single farmer to cultivate tracts of land orders of magnitude larger than a century ago. The introduction of synthetic organic pesticides in the 1940s revolutionized the control of weeds and insects. Similarly, there has been tremendous growth in the use of manufactured fertilizers and hybrid seeds. Farmers have become highly specialized in the livestock products and crops they produce, and they have become much more dependent on purchased inputs. Crops that were virtually unheard of 100 years ago, such as soybeans, are of major importance today. As agricultural productivity has risen, and as real (inflation-adjusted) prices of farm commodities have fallen, substantial acreage in the Chesapeake Bay region has been taken out of agriculture and either returned to forest or converted to urban uses.

The basic science of biotechnology is progressing very rapidly, and already tens of millions of crop acres in the U.S. have been planted with genetically modified organisms (GMOs). Plant biotechnology has the potential to yield crops with significantly greater resistance to a whole host of pests, greater resilience during periods of temperature and precipitation extremes, and even cereal varieties that fix atmospheric nitrogen in the same manner as legumes. Work is also underway to engineer pest vectors into beneficial insects as part of integrated pest management (IPM) strategies. However, GMOs with tolerance to specific herbicides are also being developed and released, and concerns have been raised that these may promote herbicide usage.

Animal biotechnology has the potential to yield livestock that process feed more efficiently, leading to reduced feeding requirements and fewer nutrients in animal wastes. Feed may also be genetically modified so as to reduce nutrients in livestock wastes. Genetically engineered vaccines and drugs could significantly reduce livestock mortality and increase yields.

Another development already underway is precision agriculture, which uses remote-sensing, computer, and information technologies in order to achieve very precise control over agricultural input applications (chemicals, fertilizers, seeds, etc.). Precision agriculture has the potential to significantly increase agricultural productivity by giving farmers much greater control over microclimates and within-field variations in soil conditions, nutrients, and pest populations (National Research Council, 1997). This may be accompanied by significant improvements in computer-based expert systems to aid farmers with production decision-making (Plucknett and Winkelmann, 1996). The environment could benefit insofar as precision agriculture permits fertilizers and pesticides to be applied more precisely where they are needed at the times of the year when they are needed.

Future increases in population in the Chesapeake Bay region may lead to additional conversion of farmland to residential and commercial uses. Future increases in per capita income could manifest themselves in larger homes and lot sizes, and thus more residential land use, a tendency evident over the last 30 to 40 years. Studies of land use confirm that population and per capita income are important determinants of the conversion of farmland and forestland to urban uses (Hardie and Parks, 1997; Bradshaw and Muller, 1998). Probable futures for the spatial pattern of development within the Chesapeake Bay region are more difficult to assess than an overall tendency toward urbanization. One possible future involves a "fill in" of areas between existing major urban centers, such as the area between Baltimore and Washington, DC (Bockstael and Bell, 1998).

At the same time, economic conditions facing agriculture in the Chesapeake Bay region can be expected to continue changing for many other reasons, including changes in global agricultural commodity prices and stricter environmental regulations toward agriculture (Abler et al., 1999). It is probable that there will be fewer commercial crop and livestock farms within the region in the future than there are today, and that some of the region's agricultural production will shift to other regions and countries (Abler et al., 1999). There may be growth in "weekend," "hobby," and other noncommercial farms within the region. However, such farms account for only a small fraction of total agricultural output   It is also probable that production per farm and yields per acre on the remaining commercial farms within the Chesapeake Bay region will be significantly higher than they are today.

5.2.4 Future Climate in the Chesapeake Bay Region

In addition to the technological and economic changes discussed above, climate in the Chesapeake Bay region is also likely to change. However, climate projections for the Chesapeake Bay region differ significantly according to the climate model used. Projections using the Hadley and GENESIS models for the Mid-Atlantic region, which includes the Chesapeake Bay region, suggest increases in average daily minimum and maximum temperatures and increases in average annual precipitation (Polsky et al., 2000). However, projections using the Canadian Climate Centre (CCC) model suggest a much warmer and drier climate than the Hadley or GENESIS models (Polsky et al., 2000).

It is very hard to predict whether extreme weather events (such as droughts, floods, heat waves, hurricanes, ice storms, blizzards, and extreme cold spells) will occur more or less often. Current trends for the Mid-Atlantic region suggest a change toward fewer extreme temperatures but more frequent severe thunderstorms and severe winter coastal storms (Yarnal, 1999). Whether these trends will continue is unclear.

5.2.5 A Simulation Model of Climate Change, Agriculture, and Water Quality

In order to assess the potential impacts of climate change on agriculture's contribution to water quality problems in the Chesapeake Bay region, we constructed a simulation model of corn production and nutrient loadings in six watersheds within the region. The model contains economic and environmental modules linking climate to productivity, production decisions by corn farmers, and nonpoint pollution loadings. Corn is an important crop to study because of its importance to the region's agriculture and because it is a major source of nutrient pollution. Corn is the most nitrogen-intensive of all major crops currently grown within the region. Livestock farms within the region also often dispose of manure on corn land.

The economic module predicts the choices that farmers make with respect to the amount of land devoted to corn and the usage of fertilizer and other inputs into corn production. Precipitation, temperature, and atmospheric carbon dioxide levels affect the uptake of fertilizer and the productivity of land used in corn production. The economic module is based on previous economic models we constructed to examine nonpoint agricultural pollution (Abler and Shortle, 1995; Shortle and Abler, 1997). We calibrated the module to the six watersheds using available state-, county-, and watershed-level data on farm production, land use, nutrient applications, and usage of other inputs.

Using the farmer decisions predicted by the economic module, the environmental module predicts nitrogen loadings from corn production within each of the six watersheds. The environmental module is based on the Generalized Watershed Loading Functions (GWLF) model (Haith et al., 1992). GWLF uses precipitation and temperature data, combined with data on land use, topography, and soil types, to estimate water runoff and pollutant concentrations flowing into streams from several types of land use, including corn. The GWLF model was calibrated to field conditions in the six watersheds by Chang, Evans, and Easterling (1999). GWLF predicts both nitrogen and phosphorous loadings. However, we found that phosphorous loadings from corn production were very highly correlated with nitrogen loadings from corn production in each watershed. Thus, we focus here on nitrogen loadings.

The locations of the six watersheds¾Clearfield Creek, Conodoquinet Creek, Juniata/Raystown River, Pequea Creek, Pine Creek, and Spring Creek¾within the Chesapeake Bay region are shown in Figure 5.1. Statistics on land cover/use for the watersheds are provided in Table 5.1, while statistics on nitrogen loadings are provided in Table 5.2. The watersheds are diverse in terms of the percentage of land devoted to agriculture as a whole and to corn. However, they are similar in that agriculture accounts for the vast majority of nonpoint nitrogen loadings. Corn alone accounts for more than half of total nonpoint nitrogen loadings in every single watershed. On average across the six watersheds, corn accounts for more than two-thirds (69%) of total nonpoint loadings.

In the simulation model, the weather is random in the sense that farmers do not know what temperature and precipitation during the growing season will turn out to be. They must therefore make planting and production decisions on the basis of average (more precisely, expected) temperature and precipitation patterns. However, farmers in the model are aware of climate change in the sense that they know how average temperature and precipitation patterns are evolving over time in their area.

We consider three climate scenarios in the model. The first is present-day climate (temperature and precipitation averages for the 1965-1994 period), which serves to establish a reference point. The second climate scenario is based on projections from the Hadley climate model for the 2025-2034 period. As noted above, the Hadley model suggests increases in average daily minimum and maximum temperatures and increases in average annual precipitation (Polsky et al., 2000). The third climate scenario is based on projections from the Canadian Climate Centre (CCC) model for the 2025-2034 period. The CCC model suggests a much warmer and drier climate than the Hadley model (Polsky et al., 2000). Because the weather is random in the model, the climate scenarios involve changes in the means and variances of the model's temperature and precipitation variables.

We also consider two future baseline scenarios in the model. These scenarios describe what might happen to corn production in the Chesapeake Bay region in coming decades independent of climate change. Shortle, Abler, and Fisher (1999) discuss procedures to use in constructing future baseline scenarios. These procedures do not attempt to predict the future, which is essentially impossible. Instead, they focus on developing scenarios that establish probable upper and lower bounds on economic and environmental impacts. That way, while it is not possible to pinpoint the exact magnitude of an impact, it is possible to say that the impact is likely to lie within a certain interval.

With an eye toward establishing probable upper and lower bounds on changes in nitrogen loadings from corn production in the Chesapeake Bay region between now and the 2025-2034 period, we consider two future baseline scenarios. These two scenarios¾a continuation of the status quo (SQ) and an "environmentally friendly," smaller agriculture (EFS)¾are detailed in Table 5.3. The EFS scenario is much more probable than any scenario approximating a continuation of the status quo, but both scenarios are needed to establish probable bounds on climate change impacts. The EFS scenario establishes a lower bound on any increase in nitrogen loadings due to climate change because biotechnology and precision agriculture help minimize loadings from any given level of agricultural production. In addition, stricter environmental regulations in the EFS scenario lead farmers to adopt less nitrogen-intensive corn production practices. None of these things occur in the SQ scenario, and so the SQ scenario establishes an upper bound on increases in nitrogen loadings due to climate change.

With three climate scenarios and two future baseline scenarios, there are a total of six ($3 \times 2 = 6$) scenario combinations to be analyzed. Because the weather is random, we analyzed each combination using a Monte Carlo experiment in which we took 100,000 random draws for the model's temperature and precipitation variables. Each of these random draws could be considered an alternative possible growing season within a particular climate scenario. The results below represent averages over the 100,000 random draws.

5.2.6 Results from the Simulation Model

Results from the simulation model for each watershed and for the six watersheds as a whole are presented in Table 5.4. Results for the six watersheds as a whole are also illustrated in Figure 5.2. The results for the SQ baseline scenario suggest that climate change could lead to significant increases in nitrogen loadings from corn production. For the six watersheds as a whole, nitrogen loadings are more than 3 million pounds higher in the Hadley climate scenario than with the present-day climate, an increase of nearly one-third (31%). In the CCC climate model scenario, nitrogen loadings for the six watersheds as a whole are nearly 2 millions pounds higher than with the present-day climate, an increase of about one-sixth (17%).

The results for the EFS baseline scenario, on the other hand, suggest that climate change would lead to more modest increases in nitrogen loadings from corn production. For the six watersheds as a whole, nitrogen loadings are about 400 thousand pounds higher in the Hadley climate model scenario than with the present-day climate, an increase of about one-fifth (19%). In the CCC climate model scenario, nitrogen loadings for the six watersheds as a whole are about 200 thousand pounds higher than with the present-day climate, an increase of only 8%.

The results for the SQ and EFS baseline scenarios differ significantly in part because the EFS scenario starts from a much lower level than the SQ scenario. Under the present-day climate, total loadings for the six watersheds as a whole are about 2 million pounds in the EFS scenario, compared to over 10 million pounds in the SQ scenario. As discussed above, there are many forces at work that cause fertilizer usage and environmental impacts to be much lower in the EFS scenario than in the SQ scenario. The results for the SQ and EFS scenarios also differ because agriculture is less climate-sensitive in the EFS scenario than in the SQ scenario.

Both the SQ and EFS baseline scenarios are in agreement, however, regarding the direction of change in nitrogen loadings from corn production. In both scenarios, climate change leads to increases in loadings. In percentage terms, the increase for the six watersheds as a whole ranges from 8% (EFS scenario/CCC climate model) to 31% (SQ scenario/Hadley climate model).

Loadings increase because climate change makes corn production in the six watersheds more economically attractive. As corn production becomes economically more attractive, farmers devote more land to corn compared with the no climate change baseline and increase their use of inputs per acre in order to raise yields. As they do these things, their usage of nitrogen fertilizer increases, leading to increases in nitrogen loadings.

The increase in growth potential of corn due to climate change in and of itself¾leaving aside for the moment the economic responses by farmers¾ leads to greater uptake of nitrogen by crops, leaving less nitrogen to run off into surface waters or leach into groundwater. However, to take full economic advantage of the growth potential of crops, farmers apply more nitrogen fertilizer. The higher nitrogen applications result in overall greater nitrogen loadings.

In the Hadley climate model scenarios, nitrogen loadings also increase because average precipitation during the growing season increases, washing more nutrients into streams, rivers, and groundwater. In the CCC climate model scenarios, on the other hand, average precipitation during the growing season falls. Nevertheless, because of the increased nitrogen applications by farmers in response to the yield effects of climate change, nitrogen loadings from corn production still increase in the CCC climate model scenarios.

5.2.7 Implications for Near-term Decisions

Two things can be done today to reduce threats to water quality in the Chesapeake Bay region created by climate change and exploit potential opportunities to improve water quality. First, federal and state governments can support research on biotechnologies and precision agriculture technologies that lead to more environmentally friendly crop and livestock production systems. The vast majority of research on biotechnology and precision agriculture is occurring in the private sector rather than the public sector, but in some cases there may not be economic incentives for the private sector to focus research on improving the environment. Land grant institutions and federal agricultural research centers can help fill this gap. Because it can take years or even decades for research to yield commercially viable new products or technologies, agricultural research belongs on today's agenda.

Second, land grant institutions within the Chesapeake Bay region can take the lead in preparing the region's current and future farmers to take advantage of future agricultural technologies. Farmers will need significant new skills, including computer skills, in order to understand and make profitable use of precision agriculture and biotechnology. This poses a major challenge for teaching and extension programs at the region's land grant institutions. Because young farmers educated today will be in the labor force for the next forty or even fifty years, education also belongs on today's agenda.

5.3 Pesticide Use and Climate

An open issue in the climate change arena involves the question: How might changes in climate might alter pest populations and in turn the costs of pest treatment? Here we summarize the results of an analysis carried out under the agricultural sector assessment by Chen and McCarl (2000) that examines how changes in climate appear to have altered current pesticide use. This analysis was based on agricultural pesticide usage data drawn from the USDA pesticide usage surveys coupled with NOAA regional weather series. We investigate the effects of climate alterations for U.S. corn, wheat, cotton, soybeans and potatoes.

5.3.2 Data

State level pesticide usage for corn, wheat, cotton, soybeans and potatoes from 1991 to 1997 were drawn from *Agricultural Chemical Usage*, USDA, ERS. These data give statistical survey based average use data for various insecticide, herbicide, and fungicide compounds by crop and year. The states for which data were available vary by crop and are listed in Table 5.5. In this study a total cost of pesticides was computed by multiplying the pesticide use by category by annual prices from the 1997 USDA *Agricultural Resources and Environmental Indicators* report. We use aggregate total cost data to reflect pesticide substitution as climate and pesticide prices vary.

Climate data were drawn from the United States National Oceanographic and Atmosphere Administration. The rainfall data used were cropping year totals to reflect not only cropping season supply but also water stored in soil or irrigation delivery systems. Temperature data used were the March to September average for all crops except for winter wheat areas. In winter wheat areas for the wheat pesticide costs we used the October to April temperature data. State level temperature and rainfall data were derived by averaging all data for weather stations in a region.

5.3.3 Methods

This study used an approach similar to that employed by Mendelsohn, Nordhaus, and Shaw, 1994. In that study geographic variation was used to consider the implications of climate for land values and to draw implications from the statistical model estimated for changes of climate in the future. In this case, we statistically evaluate how pesticide costs varied over regions and time as climatic conditions varied, using the estimated statistical model to consider future prospects for climate altered pesticide costs. Statistically we estimated a panel data version of the production function laid out by Just and Pope that allowed us to estimate both average pesticide costs and the variance of pesticide costs. For more detail, see Chen and McCarl, 2000.

5.3.4 Results

The estimated impacts of rainfall and temperature on pesticide cost and its variability by climate are displayed in Tables 5.6 to 5.9. The estimation results in Table 5.6 shows the relationship between pesticide usage costs and climate. Table 5.7 contains the computed percentage change in cost due to the per percentage change in the climate characteristics using the data in Table 5.6. The results show that the impacts of precipitation on pesticide usage cost for these five crops are all positive and significant except for cotton. This indicates that increased rainfall increases pesticide cost. For example, when rainfall increases by one percent, we compute that corn pesticide costs increase by 1.49 percent. We find mixed effect of temperature. A one percent temperature increase (measured in degrees Fahrenheit) increases pesticide costs for potatoes by 2.67 percent. Pesticide costs for corn, cotton, and soybeans also increase with temperature but wheat costs decrease.

The impacts of climate on the variability of pesticide usage cost are more complicated and are displayed in Tables 5.8 and 5.9. We found that a hotter temperature increased the variance of pesticide cost for corn, cotton and potatoes while decreasing it for soybeans and wheat. For example, the results shows that a one percent increase in temperature will increase the corn year-to-year cost variance by 6.96 percent. A rainfall increase is also found to increase the pesticide cost variability for cotton while decreasing that for soybeans, wheat and potatoes.

Under a warmer and wetter climate and given the estimated relationships, we would generally expect climate change to increase pesticide use. However, some regions may have less rainfall and, not all crops show positive relationships between the climate variables and pesticide usage. For perspective, then we used the regional estimates of the Canadian and Hadley climate scenarios for 2090 to obtain estimates of the effects of projected climate change on pesticide usage cost for selected crops in selected regions (Table 5.7). The results for those states with significant production of each crop are given in Table 5.10. They show increases in pesticide use on corn generally in the range of 10 to 20 percent, on potatoes of 5 to 15 percent and on soybeans and cotton of 2 to 5 percent. The results for wheat varied widely by state and climate scenario showing changes ranging from approximately –15 to +15 percent.

5.3.5 Pesticides and Climate: Some Conclusions

Regional pesticide cost data shows systematic variations that can be related to climate characteristics. Average per acre pesticide usage cost for corn, soybeans, wheat, and potatoes increase as precipitation increases. Similarly, average pesticide usage cost for corn, cotton, soybeans, and potatoes increase as temperature increases while the pesticide usage cost for wheat decreases. Climate also affects the year-to-year variability of pesticide cost with more rainfall decreasing cost for soybeans, wheat, and potatoes but increasing it for cotton. Increased temperature reduces the variability of pesticide cost for soybeans and wheat but increases it for corn, cotton, and potatoes. This is one of the first investigations of the relationship of pests and climate, conducted in such a way that the results could be integrated into a overall economic assessment. There are a number of limitations in the study. Among them we do not consider how altered CO_2 could effect pests and the approach considers how pesticide use changes but not how pest damage itself changes, implicitly assuming that the cost implications of any change in pests is fully captured by changes in pesticide expenditures. Projections of changes of pesticide use and climate under future climate is highly speculative as few other areas of agriculture change as rapidly as pesticides. Pests can quickly develop resistance to particular control methods and new control methods are developed. In the future, pest resistance may be increasingly introduced directly into crops. Never-the-less, these results are indicative of the fact that for most of the crops considered and for most locations, the future climate is likely to increase pest problems and create the need for more effective control methods. The environmental implications will clearly depend on the types of methods developed to control pests. The likelihood of increased pest problems creates an added incentive to ensure that methods that do not create environmental harm are developed and used.

5.4 Effects of Climatic Change on a Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer

Global climate change portends shifts in water demand and availability. In areas where water is already a severely limited resource, the potential for reductions in supply can pose significant questions with regard to the allocation of the resource remaining. Agriculture is the major user of water in most regions. Here we summarize the results of an analysis carried out under the agriculture sector assessment, described in greater detail in Chen, Gillig, and McCarl (2000). The study examines the implications of climate change projections for the San Antonio Texas, Edwards Aquifer (EA) region concentrating on the economy and the water use pattern.

This section begins with a discussion of the Edwards Aquifer area, provides a summary of the methods used to estimate the various impacts of climate on water use in the region, describes the model and methods used to consider the implications of these effects for the region, discusses the results, and offers some broader conclusions based on the study.

5.4.1 The Edwards Aquifer

The Edwards Aquifer supplies the needs of municipal, agricultural, industrial, military and recreational users. The Edwards Aquifer is a carstic aquifer that has many characteristics in common with a river. Annual recharge over the period 1934 -1996 averaged 658,200 acre feet while discharge averaged 668,700 acre feet (USGS, 1997). The Edwards Aquifer discharge is through pumping and artesian spring discharge. Pumping has risen by 1% a year in the 1970's-1980's (Collinge et al, 1993) and now accounts for 70% of total discharge. Pumping in the Western Edwards Aquifer is largely agricultural (AG) whereas eastern pumping is mainly municipal and industrial (M&I). Spring discharge, mainly from San Marcos and Comal springs in the East, supports a habitat for endangered species (Longley 1992), provides water for recreational use and serves as an important supply source for water users in the Guadalupe-Blanco river system. The aquifer is now under pumping limitations due to actions by the Texas Legislature (Texas Senate, 1993) and because of a successful suit by the Sierra club to protect the endangered species (Bunton, 1996).

Reduced water availability or increased water demand because of climate change could exacerbate the regional problems that arise in dealing with water scarcity. This study utilizes an existing Edwards Aquifer hydrological and economic systems model – EDSIM (McCarl et al. 1998) to examine the implications of climate-induced changes in recharge, and water demand.

5.4.2 Effects of Climatic Change in the Edwards Aquifer Region

The Canadian Climate Centre Model (CCC) and the Hadley Centre Model (HAD) results for the Edwards Aquifer region climate are listed in Table 5.11. Changes in regional climatic conditions would alter water demand and supply. An increase in temperature will cause an increase in water demand for irrigation and municipal use, but would also increase evaporation lowering runoff and in turn Edwards Aquifer recharge. A decrease in rainfall would increase crop and municipal water demand, lower the profitability of dryland farming and reduce the available water for recharge. Each of these terms were independently estimated and are discussed below

Recharge implications. To project climatic change effects on Edwards Aquifer recharge, a regression analysis was employed to estimate the effects of alternative levels of temperature and precipitation on historically observed recharge. Namely USGS estimates of historical recharge data by county were drawn from the Edwards Aquifer Authority annual reports for the years 1950 to 1996. County climate data for the same years were obtained from the Office of the Texas State Climatologist and a University of Utah web page. We concluded for this data set that the preferred regression model was a log-linear model. The significant recharge regressions coefficients all exhibited the expected sign. Summary measures of the effect of the projected climate changes on annual recharge for the years 2030 and 2090 under different climate scenarios is displayed in the top of Table 5.12 and shows that climate change as projected causes large reductions in recharge for drought years (21 to 33 %) and in for wet years (24 to 49 %).

Municipal water use implications. Griffin and Chang (1991) present estimates on how municipal water demand is shifted by changes in temperature and precipitation. In particular, they estimate an elasticity of climate for an increase in the municipal water demand for a one percent increase in the number of days that temperature exceeds 90 degrees and precipitation falls below 0.25 inches. To obtain the anticipated shifts for the 2030 and 2090 climate conditions, we took the daily climate record from 1950 to 1996 and adjusted it by altering the original temperature and precipitation by the projected climate shifts from the climate simulators. In turn we then recomputed the municipal water demand accordingly. The results are given in Table 5.12 where we observe that the forecasted climate change increases municipal water demand by 1.5-3.5%.

Crop yields and irrigation water use. Changes in climatic conditions influence crop yields for irrigated and dryland crops as well as irrigation crop water requirements. For this study the shift in water use and yield under the projected climate changes was estimated using the Blaney-Criddle (BC) procedure (Heims and Luckey[1983]; Doorenbos and Pruitt[1977]) following Dillon[1991]. In particular, we used the BC procedure to alter yields and water use for the 9 recharge/weather states of nature present in the EDSIM model, an economic and hydrological simulation model of the Edwards Aquifer region (McCarl et al 1998). Summary measures of the resultant effects are presented in Table 5.12 that shows a decrease in crop and vegetable yields and an increase in water requirements. For example, under the Hadley climate simulator scenario in 2090, the irrigated corn yield decreases by 3.47% whereas the irrigation water requirement increases by 31.32%.

5.4.3 Methods for Developing Regional Impact

These effects were combined in EDSIM. The model depicts pumping use by the agricultural, industrial and municipal sectors while simultaneously calculating pumping lift, ending elevation and springflow. EDSIM simulates choice of regional water use, irrigated versus dryland production and irrigation delivery system (sprinkler or furrow) such that overall regional economic value is maximized. Regional value is derived from a combination of perfectly elastic demand for agricultural products, agricultural production costs, price elastic municipal demand, price elastic industrial demand, and lift sensitive pumping costs.

In terms of its implementation EDSIM is a mathematical programming model that employs two-stage stochastic programming with recourse formulation. The multiple stages in the model depict the uncertainty inherent in regional water use decision-making. Many water related decisions are made in advance of the time when water availability is known. For example the decision whether or not to irrigate a particular parcel of land and the choice of the crops to put on that parcel are decided early in the year whereas the true magnitude of recharge is not known until substantially later during the year[1].

5.4.3 Model Experimentation, Regional Results and Discussion

Five scenarios were considered in this study: 1) BASE without climatic change, 2) the change predicted by the Hadley model for the year 2030, 3) the change predicted by the Canadian model for the year 2030; 4) the change predicted by Hadley for 2090; and 5) the change predicted by the Canadian Center model for 2090.

EDSIM results, on the economic and hydrologic effects of climate change (Table 5.14), under the BASE scenario are displayed as actual values whereas results under the other scenarios are displayed as a percentage change from the BASE results. The total water usage is held less than or equal to a 400,000 acre feet pumping limit mandated by the Texas Senate for years after 2008. Under BASE condition agriculture uses 38% of total pumping while M&I pumping usage accounts for the rest. Total welfare is $355.69 million consisting of $11.39 million from agricultural farm income and $337.65 million from M&I surplus. Additionally, $6.64 million accrues to the Edwards Aquifer Authority for the water use permits. This authority surplus can be viewed as the rents to water rights to use some of the 400,000 acre feet available. Comal and

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[1]This uncertainty is perhaps best illustrated by referring to the Irrigation Suspension Program implement by the Edwards Aquifer authority a couple of years ago where early in the year an irrigation buyout was pursued but the year turned out to be quite wet in terms of recharge.

San Marcos springflows are 379.5 and 92.8 thousand acre feet, respectively, and are greater than recent average historical levels.

According to the results the strongest effect of climate change falls on springflow and the agricultural sector. Under the climatic change scenarios the Comal (the most sensitive spring) springflows decrease by 10-16% in 2030 and 20-24% in 2090. This could require additional springflow protection as explored below. In terms of agriculture, the change results in a reallocation of water away from agriculture. It adds to the cost of pumping because the water must be pumped from greater depths and also increases water demand for irrigation because of higher temperatures and less rainfall. Overall yields are lower. The result is a reduction in farm income ranging from 16-30% in 2030 and 30-45% in 2090. Regionally income falls by 2.8 to 5 million dollars per year in 2030 and 5.8 to 8.8 million dollars in 2090. The model predicted shift in agricultural water to M&I indicates that the city users are purchasing water otherwise allocated to agricultural through water markets.

Despite an increase in M&I water use, the M&I surplus decreases. This is because of an increase in pumping costs that result from an increase in pumping lift due to lower recharge. In contrast to the decrease in welfare of agricultural and non-agricultural pumping users the rents to the authority or water permits increases by 5-24%. The increased demand for water increases the water permit prices. Water use in the nonagricultural sector is less variable and a shift to that sector actually makes water use slightly greater with corresponding declines in springflow.

The large reduction in springflow would put the endangered species in the spring emergence areas in additional peril. The projected climate change would thus require a lower pumping limit to offer the same level of protection for the springs, endangered species and other environmental amenities now provided by the 400,000 acre foot limit. Table 5.14 presents the results of an examination of the pumping limit that would be needed to preserve the same level of the Comal and San Marcos springflows as in the current situation. The results indicate that a decrease in the Edwards Aquifer pumping limit of 35 to 50 thousand acre feet in 2030 and 55 to 75 thousand acre feet in 2090 would be needed. Such further decreases in pumping impose substantial additional economic costs beyond those imposed by climate change alone with welfare falling by between 0.5 and 0.9 million dollars in 2030 and 1.1-1.9 million in 2090. The additional pumping reduction causes a large impact on agriculture and a substantial municipal cutback.

5.4.4 Concluding Remarks

The changes in climatic conditions projected by both the Canadian and Hadley center models cause a reduction in the available water resources as well as a demand increase in the San Antonio Edwards Aquifer region. The change largely manifests itself in reduced springflows and a smaller regional agricultural sector. The regional welfare loss was estimated to be between 2.2 -6.8 million dollars per year. If springflows are to be maintained at the currently desired level to protect endangered species, pumping must be reduced by 10 to 20% below the limit currently set at an additional cost of 0.5 to 2 million dollars per year.

5.5 Global Climate Change: Interactions with Soil Properties

5.5.1 Soil and Society

Soil processes operate on time scales ranging from thousands of years (e.g. breakdown of rock substrate) to hours (e.g. erosion). This fundamental resource has played an important role in human societies. The importance in our own society is summarized in an inscription on the walls of the Jefferson Memorial in Washington, " Soil is God's Gift to the Nation." Societies built by man have always required a rich soil together with a benign climate and the availability of water. Misuse of the soil resource has lead to the downfall of numerous civilizations when soil erosion, salinity and the silting of irrigation canals resulted in a slow strangulation of what had been a great resource (Laudermilk, 1975). For much of North America the climate is naturally highly variable and this variability has punished us badly when we have not been good stewards of the land. Land abandonment after excess growth of cotton in the South East, the loss of soil fertility and acidification in the North East and the dust bowl of the Prairies can be attributed to the misuse of our the soil and it's organic matter. These instances stem from a failure to recognize soil as a resource subject to degradation and to develop practices that maintain soil under climate conditions that vary from decade to decade.

Archaeological evidence indicates that a climatic factor not often considered, the CO_2 content, has throughout history had a great influence on agriculture. The domestication of animals, 120,000 to 140,000 yr ago, is said to have occurred during a period when the atmospheric CO_2 content rose from 200 to 275 :mol mol^{-1} (Sage, 1995). The domestication of plants occurred independently around the world in different cultures approximately10,000 yr ago. Humans in the Middle East domesticated lentils, barley, chick peas and wheat. Rice, millets and the Brassica spp were domesticated in the Far East 9,000 yr ago. Beans and chili peppers were grown in Meso America 8,000 yr ago. According to Sage (1995), the factor common to these widely diverse people was global climate change and the rise in the atmospheric CO_2 from 200 to 270 :mol mol^{-1}.

The 100 :mol mol^{-1} rise in CO_2 from 270 to the present level during the last 120 yr has coincided with another explosion in crop yields. The very successful plant breeding, fertilization and better pest control would not have been as effective if the major plant nutrient, i.e., carbon had not been increasing during this time. The mechanisms by which increased CO_2 affects humans, shown in Fig. 5.3, play as great a role today as they did 10,000 years ago.

5.5.2 Atmospheric Constituents and Soil Processes

The elements carbon and nitrogen oxygen and hydrogen are the building blocks of life on earth. They also are the most important constituents of soil organic matter. The earth's carbon and nitrogen cycles have the ability to restore and even increase the soils organic matter content and tilth if properly established scientific principles are applied to good land stewardship and sustainable agriculture during a time of global change.

Global change scenarios are most often associated with the predicted increases in temperature and climate instability associated with increased atmospheric concentration of gases of carbon and nitrogen. These radiative gases consist of CO_2, CH_4 and N_2O produced by microbial activities in soils, sediments, surface waters and animal digestive systems or through the burning of fossil fuels. Soil microorganisms upon breaking down plant and animal residues in environments containing oxygen produce CO_2. This returns to the air the carbon that has been fixed by photosynthesis and in the past has kept the carbon cycle in near balance. In areas where oxygen is lacking such as in peat bogs, rice fields and the stomachs of ruminants, methane (CH_4) is produced instead of CO_2.

Soil inorganic nitrogen is produced when microorganisms "burn off" the carbon of plant and animal residues or organic matter in their never ceasing search for energy. Other microorganisms oxidize, by the nitrification process, the inorganic N that is produced on mineralization or added as fertilizer. This process is leaky and produces N_2O. The oxidized form of nitrogen, NO_3 , produced during nitrification can again be reduced under anaerobic processes where there is no oxygen. This process is again leaky and can result in N_2O leakage to the atmosphere.

Methane (CH_4) is 20 time as reactive as CO_2 in retaining atmospheric heat. The gas N_2O is 300 times as reactive. The relative effect of these in causing greenhouse effects is best seen by expressing the emissions as carbon equivalents. In 1996, the USA released 1,450 million metric tons (MMT) of carbon into the atmosphere from fossil fuel consumption. This is less than one tenth that which is released annually from our soils by decomposition but the carbon of decomposition is offset by a nearly equal amount of photosynthesis while the equivalent of about one half that formed from fossil fuels accumulates in the atmosphere.

A total of 180 MMT of CH_4 equivalents is released from transportation, industry, wetlands, landfills and waste. Aerobic, terrestrial sites all absorb CH_4 but cultivated, fertilized soils consume only about one quarter that of undisturbed sites and wildlands. Agriculture is the predominant source of N_2O with transportation and industry supplying about a third as much as does agriculture. All soils release some N_2O but highly managed ones release more than do wildlands especially if they have trees. The gas CO_2 is presently increasing in the atmosphere at 0.5% per year, CH_4 at 0.75% and N_2O at 0.75%.

The clearing of forests, draining of wetlands and plowing of the prairies for agriculture lead to significant increases in atmospheric CO_2 as organic carbon was decomposed. The carbon content of most agricultural soils is now about one third less than that in its native condition as either forest or grassland. Fortunately, modern agriculture has stopped this net loss to the atmosphere (Bruce et al., 1998). This has come about through higher yields, the return of greater proportions of the crop residue to the land, conservation tillage such as cover crops and no till (Lal et al., 1998). The return of considerable acreage to grass in conservation reserve programs and to trees in afforestation of formerly plowed lands is also returning atmospheric CO_2 to the land. It is considered that the Eastern USA now has 110 million acres of afforested lands once in agriculture that are now storing carbon (Fan et al., 1998). This occurs both as tree growth and in increased soil organic matter contents (Morris et al., 1999). The other greenhouse gases, CH_4 and N_2O can also be removed from the air by soil microorganisms. Improved pastures and cover crops on cultivated land lower the amount of inorganic N in soil and can lower atmospheric radiative gases. Higher quality cattle feeds can reduce CH_4 emissions from domestic livestock.

5.5.3 Soil-Biological and Chemical Interactions in Global Change

There are a large number of agronomic-ecological interactions that occur in a world with more CO_2, higher temperatures and a more variable climate. There is great diversity of soil organisms many of which have similar functions and general decomposition reactions. This makes it possible to predict future effects of changes in soil temperature and moisture on the basis of overall controls that apply to most soil types within a major climatic area. Climate change and the accompanying extreme events will no doubt alter soil microbial populations and diversity. Given time the populations of soil biota can adapt but cataclysmic occurrences such as floods and erosion will affect the diversity of microbial populations in local areas.

The CO_2 content of soil is higher than that of the atmosphere; atmospheric concentrations of CO_2 are not expected to directly alter soil nutrient cycling. The indirect effects however have to be considered. Because of more available substrate, the symbiotic partners consisting of nitrogen fixers such as the rhizobia and the mycorrhyzal fungi should be able to obtain a greater food supply and grow more effectively with a consequent benefit to the plant. This will be especially important on forests and native grasslands, that are not normally fertilized, as they adapt to global change.

Plants are more sensitive to specific temperatures than are microorganisms. Increased temperature will move the growth requirements of specific plants 200 to 300 km north for each degree Celsius rise in temperature. This is equivalent to 60 to 90 miles for each degree Fahrenheit. This together with breeding for cold tolerance is now moving the Corn Belt into the Prairie Provinces of Canada. Insect activity of cold sensitive insects has been observed to move northward with even the slight rise in measured temperatures recently observed. With increased temperatures, we can expect to see cold temperature soil pathogens and weeds as well as fire ants in areas of what is now the Corn Belt.

Many soils contain inorganic carbon as carbonates. The pedogenic phases of these compounds can both release and sequester CO_2. Agriculture is acidifying in nature and on some soils requires the addition of lime that on solubilization releases CO_2 to the atmosphere. Soils with carbonate horizons are common in arid and semi arid regions Calcium is added as lime in dust and during the weathering of parent materials. This reacts with CO_2, based on the carbonate-bicarbonate(HCO_3^-) reactions, to produce carbonates. Soil inorganic carbon comprises approximately1700 Pg C in the surface layers. This is similar to the values quoted for organic carbon (Nordt et al., 1999) soil inorganic carbon is being leached out soils at an estimated rate of

0.25 Pg per year whereas rivers are thought to transfer 0.42 Pg C to the oceans annually providing a net CO_2 sink.

Although irrigation water release some trapped $CO_{2,}$ it is estimated that on a world wide basis soils sequester 0.16 to 0.27 Pg C yr^{-1} of atmospheric CO_2 (Holland, 1978, Bouwman and Lemans, 1995). Soil formation will be slowly altered by changes in moisture and temperature. The US is now receiving 10% more rainfall than in previous decades. Higher moisture and temperature will result in deeper profiles with more clay eluviation to lower horizons. These effects are slow and will be overshadowed by changes in management or erosion. Wind and water erosion can cause local extreme events. Agriculture has drastically changed since the dust bowl of the 1930's, but special precautions must be taken in susceptible areas when multiple year droughts with associated poor crops and high winds will again create the conditions for possible severe wind erosion whether or not this is associated with specific climate change events.

Flooding affects both agricultural and non-agricultural areas. For example, a wetter climate is expected in California with increased temperatures and more oceanic evaporation. Massive soil movement, as in soil slippage, and local flooding will be increased by more severe, local storms. Lal and Bruce (1999) estimate that 0.5 Pg C yr^{-1} are lost from local soils by erosion. Much of this is deposited within associated landscapes but 20% of this is thought to be lost to the atmosphere through accelerated decomposition. The fate of the transported carbon however is not well-known and recent estimates (Trimble, 1999) show that recent water erosion is only one sixth that which occurred during the early years of agriculture in the US Midwest.

Erosion and leaching can move extensive nutrients to rivers and eventually to estuaries. The nutrients especially nitrogen and phosphorous can create local high nutrient and thus anoxic events with serious pollution and local fish kills. This is now the case in the Mississippi Delta and Gulf of Mexico as well as in the Chesapeake Bay. The contribution of agriculture to such pollution must be determined. Possible nutrient losses in a climate-change scenario must also be considered. Nutrient management will have to include lower inputs on nitrogen and phosphorus and more containment of local floodwaters so the nutrients can soak back into the land. It must also consider the effects of extensive concentrations of both human and animal waste products on small land areas. This removes nutrients from the areas where crops are grown and often concentrates them in erosion and flood-prone areas with the potential for both eutrification and local contamination if flooding is increased with climate change.

5.5.4 Soil Organic Matter and Global Change

Organic matter constitutes from 1 to 8% of the weight of most soils and nearly all the dry weight of organic soils such as peats. Because of the great weight of soils to the plant rooting depth at which carbon accumulates, the soils of the world store 1,670,000 MMT (16.7 Pg) of carbon. This represents a carbon storage capacity that is twice that in the atmosphere. The annual global rate of photosynthesis is generally balanced by decomposition and represents one tenth of the carbon in the atmosphere or one twentieth of the carbon in soils. The US accounts for about 5%

of this storage, Canada because of its higher proportion of peat soils accounts for up to 17% (Lal et al., 1998).

Soil carbon is composed of a wide range of compounds that decompose at different rates depending on their chemistry, soil temperature and moisture, organisms present, association with soil minerals and the extent of aggregation (Paul et al., 1996). Plant residues in agricultural soils do not represent a large storage pool; their management influences water penetration, erosion and the extent of formation of soil organic matter thus affecting long term soil fertility and carbon storage.

Decomposition by soil organisms is relatively insensitive to dryness when examined on an annual basis. Most soils have some periods of time when decomposition can occur. Decomposition however is very sensitive to excess wetness that causes anaerobiosis. This in the past has created the high, organic matter peat soils. Changes in moisture content have resulted in increased decomposition of soil organic matter when the millions of acres of wetlands in the Corn Belt were tile drained (Lal et al., 1998). Warmer temperatures are often associated with drier climates. This has been postulated to greatly affect the peat soils that contain so much of North America's soil organic carbon. The drying of peat soils to below water saturation would greatly increase decomposition rates and CO_2 evolution to the atmosphere. Water saturation of soils is as much, if not more, controlled by drainage and topography as by rainfall and temperature. Predictions based on temperature-rainfall alone will not necessarily be valid relative to decomposition in peats. It is possible to control soil moisture of tile drained soils in the winter by controlling (plugging) tile drainage flows. This creates temporary wetlands and thus retards decomposition. It should have the further benefit of decreasing nitrates and possibly pesticides in the ground water as well as helping in flood control. Wetland restoration in general has potential for future carbon sequestration, providing greater diversity and havens for wildlife and reducing nitrates in ground water. It however will lead to some increases in methane and possibly N_2O evolution from the flooded soils.

Grasslands contain approximately one fifth of the world's global carbon reserves; many of the world's grasslands have been degraded by overgrazing. This has resulted in a loss of plant cover less protection against wind and water erosion and loss of production potential. Soil organic matter degradation in such conditions has contributed to the rise in atmospheric CO_2. Grazing and other management practices that lower overgrazing have the potential to increase global carbon sequestration substantially (0.46 Pg C yr^{-1}). This should also result in more methane utilization. Improvement of the cattle's diet should result in less methane production by the cattle. Fertilizer nitrogen is one of the suggested means, together with better grazing management, of increasing grassland production and soil carbon sequestration. The production of the fertilizer nitrogen however utilizes fossil fuels and its application could lead to more N_2O evolution. The closer coupling of grazing with intense animal feeding operations such that nutrients are returned for pasture improvement would greatly reduce problems with pollution when excess rainfall causes flooding.

The increased CO_2 in the atmosphere has made it possible to greatly increase yields through plant breeding, fertilizer additions and pest control. The continued predicted increase in plant yield of 1.25% per year (Reilly, 1996) will produce a similar increase in the crop residue applied to the soils. At equivalent nitrogen levels, there will be a production of more carbohydrates and possibly more lignin and polyphenols. The polyphenols should slow down decomposition rates and help build organic matter. The changed composition of leaves and roots will affect the insects and microbiota feeding on the plant parts. These are a part of a complex foodweb, often involving numerous layers of predators thus, the insect response of CO_2 should be considered in climate change scenarios.

The large size of the soil carbon pools and their slow turnover rate means that they are fairly well buffered against change and that short term effects, unless they involve erosion and thus removal of carbon from the landscape, do not have immediate effects. It usually takes 7 to 15 years of management effects to produce measurable differences in carbon and the associated soil fertility and soil tilth. The large size of the carbon pool and the fact that soil carbon is very unevenly distributed across the landscape makes it very difficult to accurately measure any changes that occur over a few years.

Total soil carbon is very difficult to measure with the accuracy required for decision making in global change calculations. Soil heterogeneity and changes in bulk density further confound the problem of measuring short-term changes in soil organic matter. Calculation of soil carbon sequestration must be based on long-term plots that have been under a specific plant management scheme for 10 to up to 30 yr. Soil fractions that are sensitive indicators of soil carbon changes are best used in conjunction with modeling that is based on a knowledge of the controls on soil carbon dynamics (Fig. 5.4). This makes it possible to predict the effect of specific management to other soil types and landscape areas.

Indicators that have been found useful include the light fraction obtained by floating soil in water or a more dense liquid. This reflects partially decomposed plant residues that make up a portion of the active fraction of soil organic matter. The microbial biomass that feeds on the residues and on the active and slow fraction of soil organic matter is another measurable fraction that changes rapidly enough to be an indicator of total changes.

The partially altered plant materials that are held within aggregates and thus slowly decompose over a period of years constitute part of the slow fraction that is so essential to soil fertility. This fraction known as particulate organic matter can be measured by disrupting the aggregates and has potential as an indicator of the overall size of the slow pool both in management for sustainable agriculture and in carbon sequestration calculations. Incubations, in the laboratory, of soils from various management treatments on different soil types and under representative climatic conditions make it possible for the soils natural population of soil fauna and soil microorganisms to decompose the different available fractions over time. Analysis of the CO_2 evolution curves makes it possible to determine the size and turnover rate of the active fraction and the slow fraction if the size of the resistant pool has previously been determined.

The above biophysical techniques are best utilized on well documented and characterized, long-term plots with known management histories where total carbon and soil bulk density can be measured to the rooting depth. If these plots are representative of the different soil types, climate, and management it is possible with mathematical models to predict the carbon content of other soils as well as the landscape. The predictions of future carbon levels are based on modeling that utilizes the information from long-term plots. The continuation of research on the long-term plots together with measurements on an array of well distributed validation plots would make it possible to plan new approaches and to support policy decisions that must be made as we adapt to global change.

5.5.6 Soils in a North American Context

The warming of North America is already noticeable in the increased growing seasons and the northward movement of the limits of corn and soybean growth. The Corn Belt will thus move into the Canadian Prairies. The soils of northern parts of Minnesota, Wisconsin, Michigan, New York, Vermont, and Maine could potentially be utilized for corn, soybeans and specialty crops. The present soils in these areas are not especially fertile and may better be left in trees both from an agroforestry viewpoint and from the aspect of removal of carbon from the atmosphere. Canada does not have a great deal of potentially useful agricultural land in the East unless it becomes so warm that the Hudson Bay lowlands would be suitable for agriculture. Warming of Western Canada will produce more agricultural land. Alberta and Northern British Columbia could develop significant underutilized acreage, that would be far from markets.

Sandy soils are much more sensitive to climatic fluctuations than the loams and clay soils. Fortunately many of the drought sensitive, sandy soils of the Great Plains have already been removed from cultivation. It is important that public policy as well as management by individual operators continue to protect these fragile soils. The extent and distribution of rainfall is the greatest unknown in future climate scenarios. It is predicted that because of higher temperatures there will be more moisture in the atmosphere and thus more rainfall on land. What is not known is where this moisture will fall. Warm periods have generally been associated with drought on the prairies. If this continues to be the case, the increased decomposition of soil organic matter due to higher temperatures will be somewhat offset by decreased decomposition due to lower moisture.

5.5.7 Field Validation

The overall requirements for soil organic matter research and field validation of the role of soil carbon in global change are:

1) Provide the analytical background and knowledge concerning the effects of agronomic management on different soil types to predict and model their effect on soil organic matter contents and other green house gases.

2) Establish benchmark sites, on a national level, that can provide verification of

treatment effects. This requires field measurements, under different management, on the soil types and climates representative of most of agricultural production accurate enough so that possible future CO_2 emission credits can be validated.

3) Provide national inventories of soil C storage and the fluxes of CO_2, N_2O and CH_4 into and out of soils.

4) Participate with available informational systems such as industry consultants and university and government extension systems to provide the necessary information to the public and the agricultural industry concerning the present and future role of soils in global change.

5.5.8 Adapting to Global Change: Policy Implications

Agriculture has had and will continue to have the ability to adapt to new scenarios. The ability to change with a changing climate will depend on a strong research base that can supply the required information. Some of the areas that may benefit the most include:

1) Crops vary in their response to enriched CO_2 in a number of growth characteristics. Research utilizing plant breeding and molecular techniques in conjunction with studies of physiological responses to increased CO_2 would increase productivity. It will also result in increased crop residue additions to the soil. The improved soil organic matter levels will sequester CO_2, enhance sustainability and reduce soil erosion. Similar techniques could be used to produce plants with increased roots and biological nitrogen fixation as well as plants with higher capacities to take up nutrients through more efficient mycorrhyza.

2) Increased phenolic and lignin contents of plant residues could decrease decomposition rates and result in more crop residues at the surface. They should also enhance the formation of the slow and resistant carbon pools important to carbon storage. The growth of more perennial crops could have many benefits especially when utilized as a biological, non-fossil fuel energy supply.

3) Irrigation efficiency can be improved. Increased oceanic temperatures should result overall in more rainfall. This can be more efficiently utilized by drip irrigation, water harvesting, and etc.

4) Develop more efficient nitrogen and phosphorus fertilizer usage, especially in flood prone areas. Precision farming holds promise for better nutrient control and pesticide application. The N,P, S and C cycles need to be considered in an ecosystem context.

5) The movement of intensive animal feeding operations to the source of the animal feeds would enhance the placement of nutrients and organic residues back on the soil and stop the development of these facilities on flood prone areas.

6) Increased soil organic matter will store more atmospheric carbon and result in greater soil fertility, better soil tilth and greater water holding capacity. It also will make plants more stress resistant and thus able to better withstand the greater predicted climatic fluctuations.

7) Control of water levels on hydric soils during periods of non-plant growth could result in C sequestration, improved water quality, flood control and better wildlife habitat. Potential losses of CH_4 and N_2O would have to be avoided.

8) Soil pathogen and pest control in a warmer, often more humid climate would have to be considered in future management scenarios.

9) Improve pasture management for better carbon sequestration.

10) Integrate farm woodlots and riparian strips into overall land management and farm policy programs that enhance both water quality and a positive response to global change.

5.5 Conclusions

Each of the cases presented above offer specific conclusions. In addition to these, five broader conclusions also emerge. First, environmental impacts can be highly dependent on the specific character of climate change. For the Chesapeake Bay, nitrogen loadings from corn production in the Chesapeake Bay region differ significantly depending on the Hadley or the Canadian Center climate scenarios are used. Similarly, McCarl, Chen, and Gillig find that available water resources in the Edwards Aquifer region of Texas differ significantly depending on whether they use projections from the Hadley model or the CCC model. In both the Chesapeake Bay region and the Edwards Aquifer region, the Hadley model projects more precipitation and less warming than does the Canadian Center climate scenario.

Second, environmental impacts are also highly dependent on the ability of crops to productively use higher atmospheric levels of carbon dioxide (CO_2). The optimistic conclusion for soils, that climate change could enhance agricultural sustainability, increase water-holding capacity, and reduce soil erosion depends on increases in crop growth as a result of additional CO_2. Results for the Chesapeake Bay region that show increased nitrogen loadings from corn production also hinges on crop responses to additional CO_2. In and of itself, a higher level of CO_2 increases nitrogen uptake by corn plants, leaving less nitrogen to run off into surface waters or leach into groundwater. Higher levels of CO_2 may make corn production in the Bay region economically more attractive. If corn production becomes more attractive, farmers may devote more land to corn and increase their use of inputs per acre in order to raise yields. If they do these things, their usage of nitrogen fertilizer may increase, leading to increases in nitrogen loadings.

Third, additional research is needed on interactions between climate, agriculture, and the environment. The vast majority of research to date on climate change and agriculture has focused on agricultural production impacts. Very little work has been done on how climate change might affect the environmental impacts of agricultural production and land use. Given the magnitudes of environmental effects in many areas of the country, this should be a high priority for research. In addition, research is needed to understand climate impacts on agriculture's contributions to wildlife habitat, rural landscape amenities, and carbon sequestration.

Fourth, particular effort is needed to investigate the potential for changes in extreme events and their consequent environmental effects. Current climate models do not adequately represent extreme weather events such as floods or heavy downpours, which can wash large amounts of fertilizers, pesticides, and animal manure into surface waters. Changes in extreme events could easily overwhelm the environmental effects of changes in average levels of precipitation or temperature as well as the effects of changing atmospheric CO_2 levels.

Fifth, many of these environmental and conservation concerns involve non-market, off-farm effects and require actions by local, regional, or Federal governments if these resources are to be protected. The first step in many cases is that adequate protection measures are needed to protect environmental resources under current climate conditions. Climate change may mean that managers need to be prepared to adapt the protection measures if climate change makes them inadequate. The Chesapeake Bay study indicates that the current management of these resources can be inadequate. The long-term quality of these resources may be affected by climate change, but improving agricultural practices under current climate would offer significant improvement under the current climate. Such changes also greatly reduced pollution under both climate change scenarios considered. The other side of this story is illustrated in the Edwards Aquifer study where a pumping limit imposed with the expectation of maintaining the health of ecosystems and protecting endangered species may prove inadequate by a significant margin if the climate changes as projected by the scenarios we considered.

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Table 5.1. Land Cover/Use in the Six Study Watersheds

Watershed	Land Area (1000 Acres)			Percentage of Total Land Area	
	Total	**All Agriculture**	**Corn**	**All Agriculture**	**Corn**
Clearfield Creek	240	33	8	14%	3%
Conodoquinet	321	199	24	62%	7%
Juniata/ Raystown	458	154	40	34%	9%
Pequea Creek	98	70	9	71%	9%
Pine Creek	629	66	27	11%	4%
Spring Creek	44	21	13	49%	31%
All Six Watersheds	1789	543	120	30%	7%

Sources: Chang, Evans, and Easterling (1999) and authors' own calculations.

Note: Figures for the six watersheds may not add to the column totals shown in the last row because of rounding.

Table 5.2. Nonpoint Nitrogen Loadings in the Six Study Watersheds

Watershed	Nonpoint Inorganic Nitrogen Loadings (1000 Pounds)			Percentage of Total Nonpoint Nitrogen Loadings	
	Total	All Agriculture	Corn	All Agriculture	Corn
Clearfield Creek	2057	1852	1453	90%	71%
Conodoquinet	5102	5023	2914	98%	57%
Juniata/ Raystown	4359	4261	3661	98%	84%
Pequea Creek	1335	1327	940	99%	70%
Pine Creek	1623	1317	981	81%	60%
Spring Creek	709	697	587	98%	83%
All Six Watersheds	15192	14481	10536	95%	69%

Source: Authors' own calculations.

Note: Figures for the six watersheds may not add to the column totals shown in the last row because of rounding.

Table 5.3. Baseline Agricultural Scenarios for the 2035-2034 Period

Scenario	Scenario Details
"Environmentally Friendly," Smaller Agriculture (EFS)	· Significant decline in corn production in Chesapeake Bay region · Significant decrease in number of commercial corn farms in region · Substantial increase in agricultural productivity due to biotechnology and precision agriculture · Major increase in corn production per farm and corn yields on remaining commercial farms · Significant decrease in agriculture's sensitivity to climate variability due to biotechnology and precision agriculture · Continued conversion of agricultural land to urban uses, with some abandonment of unprofitable agricultural land · Significant decrease in commercial fertilizer and pesticide usage due to biotechnology · Less runoff and leaching of agricultural nutrients and pesticides due to precision agriculture · Stricter environmental regulations facing agriculture
Status Quo (SQ)	Agriculture as it exists today in the Chesapeake Bay region

Table 5.4. Nitrogen Loadings from Corn Production under Alternative Scenarios (1000 Pounds)

Watershed	Baseline/Climate Scenario Combination					
	Status Quo (SQ)			Environmentally Friendly, Smaller Agriculture (EFS)		
	Present-Day Climate	Hadley Climate Model	CCC Climate Model	Present-Day Climate	Hadley Climate Model	CCC Climate Model
Clearfield Creek	1453	1913	1710	313	374	340
Conodoquinet	2914	3835	3426	629	750	681
Juniata/ Raystown	3661	4803	4294	788	938	855
Pequea Creek	940	1242	1108	203	243	221
Pine Creek	981	1285	1150	211	251	229
Spring Creek	587	771	689	126	151	137
All Six Watersheds	10536	13848	12377	2270	2706	2462

Source: Results from authors' simulation model.

Note: The figures shown for each scenario are averages across 100,000 random samples. Figures for the six watersheds may not add to the column totals shown in the last row because of rounding.

Table 5.5 States for Which Pesticide Data Are Available by Crop

Crop	State
CORN	IL, IN, IA, MI, MN, MO, NE, OH, SD, WI.
COTTON	AZ, AR, CA, LA, MS, TX.
SOYBEANS	AR, IL, IN, IA, LA, MN, MS, MO, NE, OH, TN.
WHEAT	CO, ID, KS, MN, MT, ND, NE, OK, OR, SD, TX, WA.
POTATOES	CO, ID, ME, MI, MN, NY, ND, OR, PA, WA, WI.

Table 5.6 Regression Results for Effects of Climate on Per Acre Pesticide Cost

Crop	Precipitation	Temperature	Constant
CORN	0.7351	0.9222	-30.183
	(25.85)	(19.00)	(-11.30)
COTTON	0.0059	0.9730	-17.213
	(0.26)	(8.39)	(-2.27)
SOYBEANS	0.0632	0.5523	32.343
	(3.78)	(13.22)	(15.04)
WHEAT	0.1211	-0.1160	7.7950
	(29.25)	(-21.30)	(24.41)
POTATOES	1.3684	2.5914	-89.564
	(22.76)	(11.99)	(-7.54)

(Note): Temperature is measured in degrees Fahrenheit and rainfall is measured in inches. T-statistics in parentheses indicate significance of all estimates except for cotton, where the precipitation and temperature coefficients are insignificant at the 5 percent level.

Table 5.7 Percentage Change in Pesticide Cost for a One Percent Change in Average Climate Measures (percentage)

	Precipitation	Temperature
CORN	1.49	1.87
COTTON		1.94
SOYBEANS	0.09	0.78
WHEAT	2.86	-2.74
POTATOES	1.41	2.67

(Note):The percentage change for pesticide cost is computed by dividing the coefficient parameters in table 5.6 by the U.S. average pesticide cost for a crop across all years and places.

Results are only computed for estimated parameters with t ratios which exceed 1.9.

Temperature percentage change is based on degrees Fahrenheit and rainfall percentage is based on inches.

Table 5.8. Regression Results on Influence of Climate on Variance of Pesticide Usage Cost

	Precipitation	Temperature	Constant
CORN	-0.0008	0.1179	-6.2453
	(-0.22)	(19.56)	(-19.93)
COTTON	0.0093	0.0497	-2.1377
	(4.03)	(3.65)	(-2.42)
SOYBEANS	-0.0190	-0.0500	4.4399
	(-7.52)	(-8.96)	(16.33)
WHEAT	-0.0489	-0.0225	0.4838
	(-25.45)	(-7.15)	(2.83)
POTATOES	-0.0372	0.1273	-3.4946
	(-12.00)	(8.25)	(-4.02)

(Note): Temperature is measured in degrees Fahrenheit and rainfall is measured in inches.

Table 5.9 Percentage Change in Variance of Pesticide Usage Cost for a One percent Change in Average Climate Measures

	Precipitation	Temperature
CORN		6.96
COTTON	0.39	3.44
SOYBEANS	-0.83	-3.20
WHEAT	-1.33	-1.34
POTATOES	-1.15	7.14

(Note): The percentage change for pesticide variability cost is computed by multiplying the coefficient parameters in table 5.8 by the average precipitation and temperature across all years and places.

Results are only computed for estimated parameters with t ratios which exceed 1.9.

Temperature percentage change is based on degrees Fahrenheit and rainfall percentage is based on inches.

Table 5.10 Percentage Increase in Crop Pesticide Usage Cost for 2090 Year by Scenario

	Canadian Climate Change Scenario					Hadley Climate Change Scenario				
	Corn	Soyb.	Cott	Wht	Pota.	Corn	Soyb.	Cott	Wht	Pota.
CA			5.16					4.69		
CO				-10.29	7.33				9.15	13.25
GA			4.23					2.66		
ID					21.03					15.42
IL	18.19	3.26				14.23	2.00			
IN	10.01	2.72				15.07	2.04			
IA	26.07	3.94				15.66	2.17			
KS				13.60					12.93	
LA			5.36					3.12		
MN		2.25			8.10		1.90			9.67
MT				-9.85					6.28	
MS			5.83					3.01		
ND					5.54					10.67
NE	3.35	2.69		-14.54		10.72	2.16		5.83	
OK				-3.48					12.34	
SD	17.08			8.88		14.73			13.96	
TX			5.41	-8.78				3.15	0.81	
WA					13.19					10.68

Table 5.11 Projected Percentage Climate Changes for Edwards Region by Scenario

Climate Change Scenario	Temperature (^{0}F)	Precipitation
Hadley 2030	3.20	-4.10
Hadley 2090	9.01	-0.78
Canadian 2030	5.41	-14.36
Canadian 2090	14.61	-4.56

Table 5.12 Selected Effects under the Climate Scenario in terms of Percentage Changes from the BASE Scenario

	Hadley		Canadian	
	2030	2090	2030	2090
Recharge in drought year	-20.59	-32.89	-29.65	-31.96
Recharge in normal year	-19.68	-33.46	-28.99	-36.23
Recharge in wet year	-23.64	-41.45	-34.42	-48.86
Municipal Water demand	1.539	2.521	1.914	3.468
Irrigated Corn Yield	-1.93	-3.47	-4.26	-5.61
Irrigated Corn Water Use	11.95	31.32	23.47	54.03
Dryland Corn Yield	-3.93	-6.78	-8.17	-10.79
Irrigated Sorghum Yield	-1.75	-3.35	-2.79	-4.17
Irrigated Sorghum Water Use	15.12	38.16	42.65	79.36
Dryland Sorghum Yield	-5.93	-13.07	-10.82	-16.76
Irrigated Cotton Yield	-9.06	-15.82	-19.80	-24.64
Irrigated Cotton Water Use	16.88	40.82	34.58	71.50
Dryland Cotton Yield	-7.13	-11.60	-13.95	-17.76
Irrigated Cantaloupe Yield	-1.34	-2.33	-2.86	-3.58
Irrig. Cantaloupe Water Use	18.95	46.47	41.41	82.68
Irrigated Cabbage Yield	-5.57	-12.05	-9.63	-14.72
Irrigated Cabbage Water Use	14.80	30.95	36.36	71.30

Table 5.13 Aquifer regional Results under alternative Climate Change Scenarios

Variable	Units	BASE Value	2030 Hadley (%)	2030 Canadian (%)	2090 Hadley (%)	2090 Canadian (%)
AG Water Use [a]	1000 af	150.05	-0.89	-1.35	-2.4	-4.15
M&I Water Use [b]	1000 af	249.72	0.63	0.9	1.54	2.59
Total Water Use [c]	1000 af	399.77	0.06	0.06	0.06	0.06
Net AG Income [d]	Thousand Dollars	11391	-15.85	-29.41	-30.34	-44.97
Net M&I Surplus [e]	Thousand Dollars	337657	-0.2	-0.36	-0.58	-0.92
Authority Surplus [f]	Thousand Dollars	6644	3.76	7.07	12.73	21.6
Net Total Welfare [g]	Thousand Dollars	355692	-0.64	-1.16	-1.3	-1.93
Comal Flow [h]	1000 af	379.5	-9.95	-16.62	-20.15	-24.15
San Marcos Flow [i]	1000 af	92.8	-5.07	-8.3	-10.09	-12.06

[a] refers to agricultural water use.
[b] refers to municipal and industrial water use.
[c] refers to total water use including agricultural and non-agricultural water use.
[d] refers to net farmer income.
[e] refers to net municipal and industrial surplus.
[f] refers to surplus accruing to the pumping or springflow limit.
[g] refers to net total welfare including agricultural and non-agricultural welfare.
[h] refers to Comal springflow.
[i] refers to San Marcos springflow.

Table 5.14 Results of Analysis on Needed Pumping Limit to Preserve Springflows at Base, without Climate Change Levels

		BASE	2030		2090	
Variable	Units	Value	Hadley (%)	Canadian (%)	Hadley (%)	Canadian (%)
Pumping Limit	1000 af	400	365	350	345	320
AG Water Use	1000 af	150.05	-16.46	-22.74	-23.69	-46.08
M&I Water Use	1000 af	249.72	-4.03	-6.27	-7.7	-4.26
Total Water Use	1000 af	399.77	-8.7	-12.45	-13.7	-19.95
Net AG Income	Thousand Dollars	11391	-18.43	-33.44	-34.6	-58.28
Net M&I Surplus	Thousand Dollars	337657	-0.78	-1.3	-1.86	-1.88
Authority Surplus	Thousand Dollars	6644	32.33	52.53	73.66	68.34
Net Total Welfare	Thousand Dollars	355692	-0.78	-1.41	-1.62	-2.47
Comal Flow	1000 af	379.5	1.47	0.52	1.22	-1.06
San Marcos Flow	1000 af	92.8	-0.28	-1.13	-1.11	-2.48

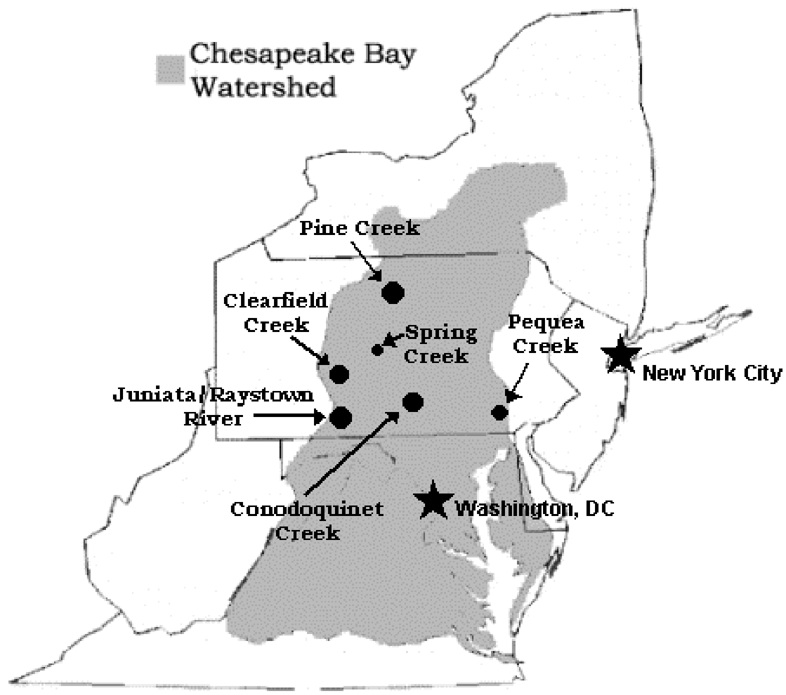
Note: The pumping limit under each scenario represents the amount of water restriction in Edwards Aquifer regions.

Table 5.15. Trends in U.S. Greenhouse Gas Emissions
(Million metric tonnes carbon equivalents)

Category	1990	1996
CO_2		
Fossil fuel combustion	1330	1450
Other industrial sources	20	20
CH_4		
Transportation & industry	60	60
Landuse & agriculture	50	50
Landfills & waste	60	70
N_2O		
Transportation & industry	30	30
Landuse & agriculture	65	70
HFCs, PFCs, SF_6	20	35
Total	**1635**	**1785**

Source: U.S. EPA

Figure 5.1. Chesapeake Bay Region and Study Watersheds



Sources: Chesapeake Bay Program (1997) and Chang, Evans, and Easterling (1999).

Figure 5.2 Nitrogen Loadings from Corn Production for the Six Watersheds

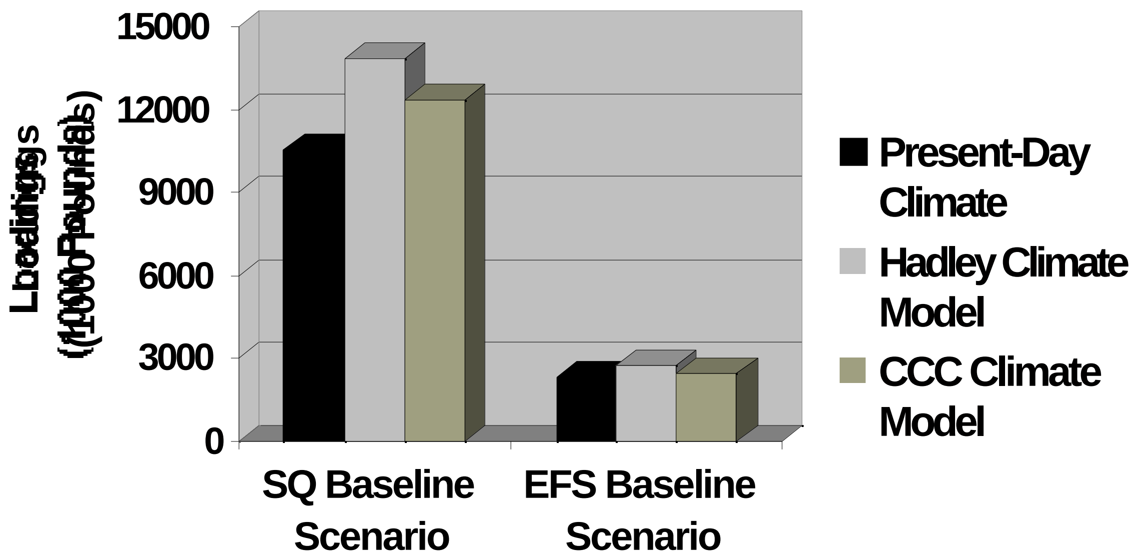
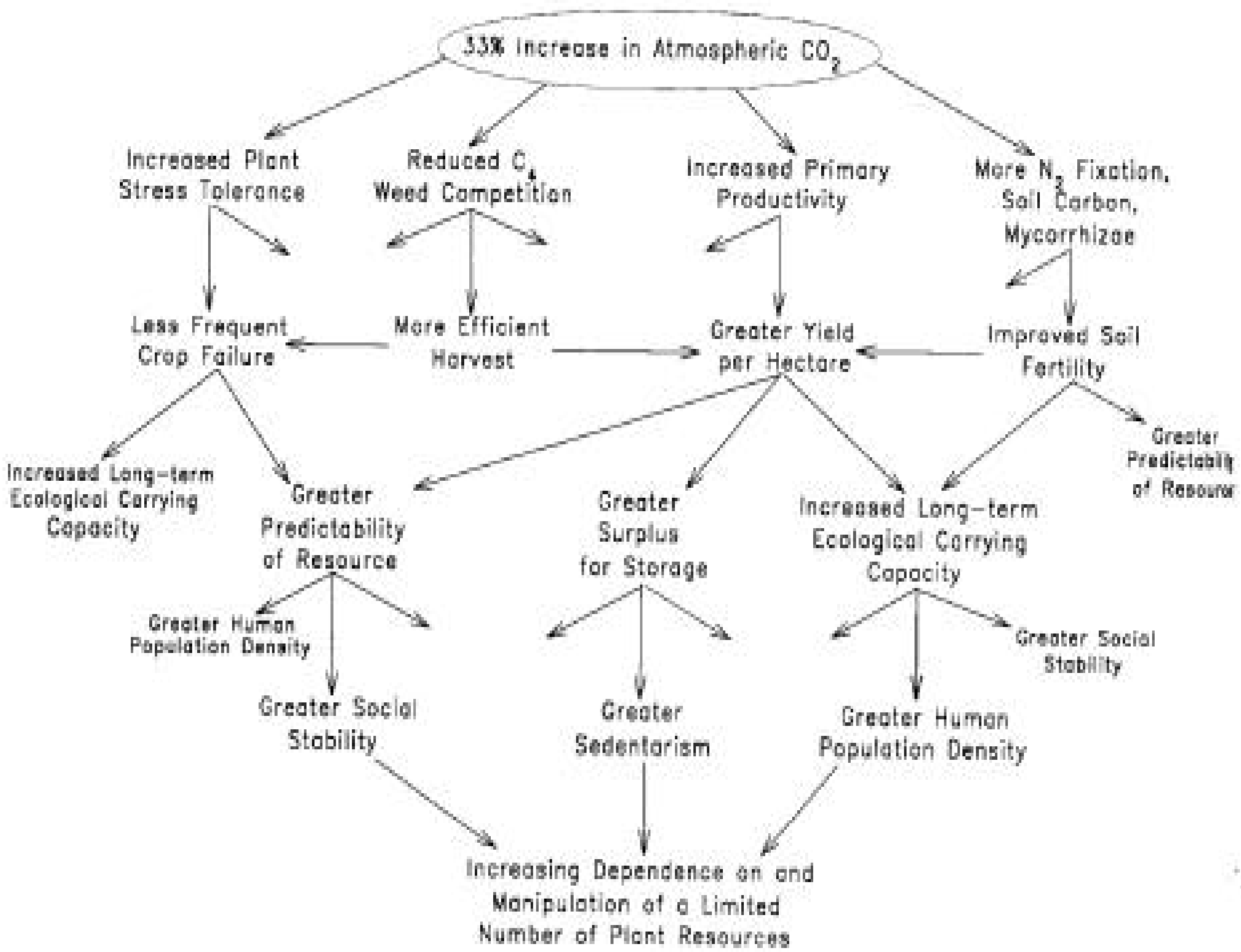


Figure 5.3 Possible linkages between an increase in atmospheric CO_2 from 200 to 270 :mol mol^{-1} and increased human specialization on a limited number of plant resources. (From Sage, 1995)



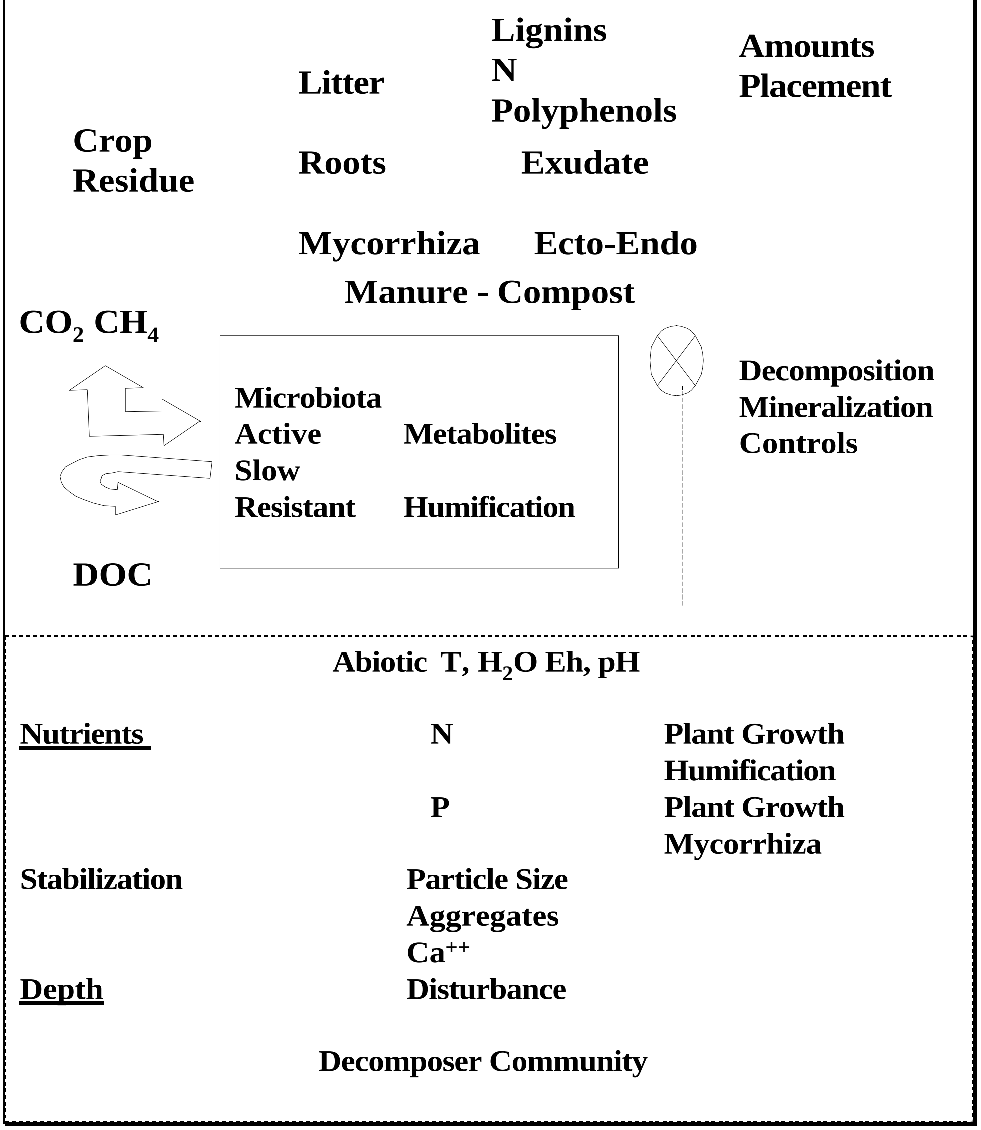


Figure 5.4. Controls on Soil Carbon Turnover and Accumulation